Supplementary materials for:

**Monitoring bird migration using nocturnal flight calls on the East Asian-Australasian Flyway: a case from Beijing**

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**Figure S1** Habitat associations of migratory birds recorded in this study. Each column corresponds to a ‘habitat association guild’, with the dark-coloured cells in the middle matrix indicating the habitats with which species or species groups in a given guild are associated. Bars above the matrix represent the numbers of species or species groups that fall within each habitat association guild, while bars below the matrix represent the total numbers of NFCs recorded for all the species or species groups in each habitat association guild.



**Figure S2** Comparison of weather features among the four study seasons, including (A) dew point temperature (℃), (B) wind speed (m/s; on natural log scale), (C) air temperature (℃), and (D) sea level pressure (hPa). The numbers above the violin plots indicate the mean values of each weather feature within a given migration season. The significance level of each pair-wise comparison (after Bonferroni correction) of the weather features is presented above the lines connecting each pair of violin plots.



**Figure S3** Comparison of the mean loudness (measured in sone; on natural log scale) among the four study seasons. The numbers above the violin plots indicate the mean values within a given migration season. The significance level of each pair-wise comparison (after Bonferroni correction) of the loudness measures is presented above the lines connecting each pair of violin plots.

**Figure S4** Temporal patterns of migratory phenology of additional species or species groups that had ≥150 NFCs over at least one migration season (not including common local breeders or the Siberian Rubythroat *Calliope calliope*), based on the number of records from NFC monitoring and citizen science observations, including (A) Brambling *Fringilla montifringilla*, (B) Eastern Yellow Wagtail *Motacilla tschutschensis*, (C) Great Bittern *Botaurus stellaris*, (D) Little Bunting *Emberiza pusilla*, (E) Richard’s Pipit *Anthus richardi*, (F) Siberian Accentor *Prunella montanella*, (G) *Anser* spp. (geese) and (H) *Emberiza* spp. (buntings). Line width indicates the rescaled number of calls or checklists, aggregated over five-day periods. Line colour indicates data resource, with grey colour representing zero counts. For Little Bunting, we grouped calls together with other bunting calls in autumn 2021 and spring 2022; we thus had data only for autumn 2022 and spring 2023.



**Figure S5** Total number of bird observation checklists (including incomplete checklists) by month between 2002 and 2022, from two main citizen science databases.

**Table S1** Call counts from all recording hours and bona fide night during each migration season for each species or species group. List of species or species groups follows a descending order based on the total number of calls across the four study seasons.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Common name** | **Scientific name** | 2021 autumn | 2022 spring | 2022 autumn | 2023 spring | Total |
| All | Night | Adjusted† | All | All | Night | All | Night | All | Night |
| **Species** |  |  |  |  |  |  |  |  |  |  |  |
| Olive-backed Pipit | *Anthus hodgsoni* | 12468 | 11547 | 10054 | 393 | 12689 | 12402 | 608 | 407 | 26158 | 24749 |
| Black-crowned Night-Heron | *Nycticorax nycticorax* | 5358 | 4550 | 1836 | 425 | 2152 | 1608 | 529 | 467 | 8464 | 7050 |
| Common Rosefinch | *Carpodacus erythrinus* | 2124 | 1591 | 1375 | 486 | 2137 | 1921 | 3096 | 2730 | 7843 | 6728 |
| Eurasian Skylark | *Alauda arvensis* | 2614 | 2568 | 2351 | 5 | 1354 | 1323 | 843 | 808 | 4816 | 4704 |
| Red-rumped Swallow | *Cecropis daurica* | 252 | 0 | 0 | 0 | 4451 | 1 | 0 | 0 | 4703 | 1 |
| Little Bunting | *Emberiza pusilla* | 0 | 0 | 0 | 0 | 1204 | 1175 | 488 | 278 | 1692 | 1453 |
| Brambling | *Fringilla montifringilla* | 328 | 314 | 208 | 21 | 1069 | 967 | 147 | 142 | 1565 | 1444 |
| Yellow-bellied Tit | *Periparus venustulus* | 549 | 354 | 237 | 2 | 29 | 19 | 162 | 104 | 742 | 479 |
| Indian Cuckoo | *Cuculus micropterus* | 0 | 0 | 0 | 428 | 20 | 18 | 293 | 253 | 741 | 699 |
| Grey Heron | *Ardea cinerea* | 108 | 95 | 74 | 77 | 369 | 364 | 118 | 109 | 672 | 645 |
| Little Grebe | *Tachybaptus ruficollis* | 6 | 6 | 5 | 178 | 171 | 158 | 202 | 198 | 557 | 540 |
| Richard’s Pipit | *Anthus richardi* | 266 | 228 | 224 | 25 | 98 | 83 | 51 | 18 | 440 | 354 |
| Eastern Yellow Wagtail | *Motacilla tschutschensis* | 261 | 118 | 26 | 11 | 76 | 23 | 22 | 0 | 370 | 152 |
| White Wagtail | *Motacilla alba* | 204 | 41 | 12 | 4 | 22 | 3 | 94 | 1 | 324 | 49 |
| Siberian Rubythroat‡ | *Calliope calliope* | 85 | 85 | 85 | 1 | 236 | 236 | 0 | 0 | 322 | 322 |
| Siberian Accentor | *Prunella montanella* | 123 | 101 | 48 | 2 | 171 | 101 | 9 | 9 | 305 | 213 |
| Eurasian Coot | *Fulica atra* | 0 | 0 | 0 | 36 | 17 | 15 | 208 | 208 | 261 | 259 |
| Silver-throated Tit | *Aegithalos glaucogularis* | 248 | 241 | 1 | 0 | 0 | 0 | 0 | 0 | 248 | 241 |
| Common Swift | *Apus apus* | 0 | 0 | 0 | 0 | 0 | 0 | 246 | 0 | 246 | 0 |
| Black-winged Stilt | *Himantopus himantopus* | 0 | 0 | 0 | 7 | 2 | 2 | 229 | 229 | 238 | 238 |
| Great Bittern | *Botaurus stellaris* | 20 | 19 | 16 | 3 | 175 | 174 | 14 | 14 | 212 | 210 |
| Striated Heron | *Butorides striata* | 48 | 48 | 42 | 55 | 56 | 55 | 51 | 50 | 210 | 208 |
| Common Moorhen | *Gallinula chloropus* | 0 | 0 | 0 | 60 | 11 | 11 | 132 | 132 | 203 | 203 |
| Pine Bunting | *Emberiza leucocephalos* | 37 | 24 | 11 | 0 | 109 | 84 | 0 | 0 | 146 | 108 |
| Wood Sandpiper | *Tringa glareola* | 1 | 1 | 1 | 2 | 117 | 115 | 6 | 6 | 126 | 124 |
| Common Sandpiper | *Actitis hypoleucos* | 10 | 10 | 9 | 13 | 43 | 43 | 59 | 59 | 125 | 125 |
| Green Sandpiper | *Tringa ochropus* | 42 | 39 | 37 | 12 | 23 | 20 | 39 | 34 | 116 | 105 |
| Buff-bellied Pipit | *Anthus rubescens* | 18 | 9 | 0 | 1 | 19 | 8 | 49 | 0 | 87 | 18 |
| Little Ringed Plover | *Charadrius dubius* | 1 | 1 | 1 | 17 | 17 | 17 | 51 | 51 | 86 | 86 |
| Yellow-throated Bunting | *Emberiza elegans* | 29 | 0 | 0 | 0 | 54 | 8 | 0 | 0 | 83 | 8 |
| Carrion Crow | *Corvus corone* | 18 | 0 | 0 | 0 | 0 | 0 | 64 | 0 | 82 | 0 |
| Pallas’s Reed Bunting | *Emberiza pallasi* | 28 | 17 | 10 | 0 | 39 | 37 | 0 | 0 | 67 | 54 |
| Forest Wagtail | *Dendronanthus indicus* | 23 | 0 | 0 | 3 | 12 | 0 | 0 | 0 | 38 | 3 |
| Daurian Jackdaw | *Corvus dauuricus* | 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 33 | 0 |
| Asian Koel | *Eudynamys scolopaceus* | 0 | 0 | 0 | 9 | 0 | 0 | 20 | 20 | 29 | 29 |
| Red-throated Pipit | *Anthus cervinus* | 3 | 0 | 0 | 0 | 24 | 4 | 1 | 0 | 28 | 4 |
| Spotted Redshank | *Tringa erythropus* | 7 | 7 | 3 | 0 | 10 | 10 | 10 | 10 | 27 | 27 |
| Long-billed Plover | *Charadrius placidus* | 25 | 25 | 25 | 0 | 0 | 0 | 0 | 0 | 25 | 25 |
| Tristram’s Bunting | *Emberiza tristrami* | 0 | 0 | 0 | 0 | 25 | 13 | 0 | 0 | 25 | 13 |
| Lapland Bunting | *Calcarius lapponicus* | 9 | 9 | 9 | 0 | 14 | 14 | 0 | 0 | 23 | 23 |
| Blyth’s Pipit | *Anthus godlewskii* | 3 | 3 | 3 | 0 | 18 | 15 | 1 | 0 | 22 | 18 |
| Purple Heron | *Ardea purpurea* | 13 | 13 | 12 | 1 | 8 | 8 | 0 | 0 | 22 | 22 |
| Black-capped Kingfisher | *Halcyon pileata* | 0 | 0 | 0 | 9 | 5 | 5 | 7 | 7 | 21 | 21 |
| Caspian Tern | *Hydroprogne caspia* | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 19 | 19 | 19 |
| Chinese Penduline Tit | *Remiz consobrinus* | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 0 | 19 | 0 |
| Brown Shrike | *Lanius cristatus* | 4 | 4 | 4 | 2 | 4 | 4 | 4 | 4 | 14 | 14 |
| Barn Swallow | *Hirundo rustica* | 10 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 13 | 0 |
| Grey Plover | *Pluvialis squatarola* | 3 | 3 | 0 | 8 | 0 | 0 | 0 | 0 | 11 | 11 |
| Grey-headed Lapwing | *Vanellus cinereus* | 8 | 8 | 8 | 0 | 0 | 0 | 3 | 3 | 11 | 11 |
| White’s Thrush | *Zoothera aurea* | 0 | 0 | 0 | 10 | 1 | 1 | 0 | 0 | 11 | 11 |
| Bewick’s Swan | *Cygnus columbianus* | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 0 | 10 | 10 |
| Grey Wagtail | *Motacilla cinerea* | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 |
| Oriental Reed Warbler | *Acrocephalus orientalis* | 0 | 0 | 0 | 5 | 0 | 0 | 4 | 3 | 9 | 8 |
| Large Hawk-Cuckoo | *Hierococcyx sparverioides* | 0 | 0 | 0 | 8 | 0 | 0 | 34 | 19 | 42 | 27 |
| Large-billed Crow | *Corvus macrorhynchos* | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 |
| Rustic Bunting | *Emberiza rustica* | 0 | 0 | 0 | 0 | 8 | 6 | 0 | 0 | 8 | 6 |
| Black-faced Bunting | *Emberiza spodocephala* | 7 | 7 | 7 | 0 | 0 | 0 | 0 | 0 | 7 | 7 |
| Garganey | *Spatula querquedula* | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 7 |
| Yellow-billed Grosbeak | *Eophona migratoria* | 7 | 7 | 7 | 0 | 0 | 0 | 0 | 0 | 7 | 7 |
| Common Cuckoo | *Cuculus canorus* | 0 | 0 | 0 | 3 | 0 | 0 | 3 | 3 | 6 | 6 |
| Ashy Minivet | *Pericrocotus divaricatus* | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 5 | 0 |
| Common Greenshank | *Tringa nebularia* | 1 | 1 | 1 | 3 | 0 | 0 | 1 | 1 | 5 | 5 |
| Little Whimbrel | *Numenius minutus* | 5 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 5 | 5 |
| Mallard | *Anas platyrhynchos* | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 5 | 5 |
| Common Redshank | *Tringa totanus* | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 0 | 4 | 4 |
| Pacific Golden Plover | *Pluvialis fulva* | 0 | 0 | 0 | 1 | 3 | 1 | 0 | 0 | 4 | 2 |
| Peregrine Falcon | *Falco peregrinus* | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 | 0 |
| Siberian Thrush§ | *Geokichla sibirica* | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 0 | 4 | 4 |
| Brown-cheeked Rail | *Rallus indicus* | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 3 |
| Far Eastern Curlew§ | *Numenius madagascariensis* | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 0 |
| Oriental Scops Owl | *Otus sunia* | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 3 | 3 |
| Pied Avocet | *Recurvirostra avosetta* | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 3 |
| Water Pipit | *Anthus spinoletta* | 1 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 3 | 2 |
| Eurasian Curlew | *Numenius arquata* | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 2 | 2 |
| Grey Nightjar | *Caprimulgus jotaka* | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 2 |
| Grey-tailed Tattler | *Tringa brevipes* | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| Whimbrel | *Numenius phaeopus* | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 2 | 2 |
| Black-naped Oriole | *Oriolus chinensis* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| Citrine Wagtail | *Motacilla citreola* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| Common Snipe | *Gallinago gallinago* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| Common Tern | *Sterna hirundo* | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Kentish Plover | *Charadrius alexandrinus* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| Northern Shoveler | *Spatula clypeata* | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Relict Gull | *Ichthyaetus relictus* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| Rosy Pipit | *Anthus roseatus* | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Ruddy Shelduck | *Tadorna ferruginea* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| Taiga Flycatcher | *Ficedula albicilla* | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Two-barred Warbler | *Phylloscopus plumbeitarsus* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| White-breasted Waterhen | *Amaurornis phoenicurus* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| Yellow-breasted Bunting | *Emberiza aureola* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| **Species group** |  |  |  |  |  |  |  |  |  |  |  |
| Buntings†† | *Emberiza spp.* | 4243 | 2858 | 2257 | 559 | 966 | 673 | 487 | 336 | 6255 | 4426 |
| Flycatchers‡‡ | Muscicapidae spp. | 857 | 855 | 827 | 0 | 2282 | 2278 | 963 | 955 | 4102 | 4088 |
| White-eyes | *Zosterops spp.* | 1566 | 1351 | 367 | 122 | 712 | 631 | 293 | 150 | 2693 | 2254 |
| Thrushes | Turdidae spp. | 908 | 905 | 888 | 49 | 380 | 379 | 81 | 81 | 1418 | 1414 |
| Geese | *Anser spp.* | 0 | 0 | 0 | 43 | 1086 | 1086 | 19 | 19 | 1148 | 1148 |
| Herons or bitterns | Ardeidae spp. | 7 | 7 | 7 | 154 | 543 | 491 | 201 | 191 | 905 | 843 |
| Wagtails or pipits§§ | Motacillidae spp. | 0 | 0 | 0 | 18 | 284 | 115 | 125 | 6 | 427 | 139 |
| Songbirds | Passeriformes spp. | 0 | 0 | 0 | 0 | 0 | 0 | 417 | 356 | 417 | 356 |
| Winter thrushes | *Turdus spp.* | 59 | 58 | 56 | 1 | 98 | 98 | 1 | 1 | 159 | 158 |
| Snipes | *Gallinago spp.* | 2 | 2 | 2 | 1 | 12 | 12 | 42 | 42 | 57 | 57 |
| Wagtails | *Motacilla spp.* | 13 | 6 | 1 | 0 | 0 | 0 | 16 | 0 | 29 | 6 |
| Rails or crakes | Rallidae spp. | 0 | 0 | 0 | 0 | 1 | 1 | 18 | 18 | 19 | 19 |
| Pipits | *Anthus spp.* | 8 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 8 | 1 |
| Swifts | *Apus spp.* | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 0 | 9 | 0 |
| Crows | Corvidae spp. | 1 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 8 | 0 |
| Larks | Alaudidae spp. | 0 | 0 | 0 | 0 | 5 | 5 | 0 | 0 | 5 | 5 |
| Shorebirds | Charadriiformes spp. | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 5 | 5 |
| Cuckoos | *Cuculus spp.* | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 2 | 3 | 3 |
| Ducks | *Anas spp.* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| Ducks or geese | Anseriformes spp. | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Richard’s or Blyth’s Pipit | *Anthus richardi/godlewskii* | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| 　 | 　 |  |  |  |  |  |  |  |  |  |  |
| Unidentified calls |  | 1557 | 1334 | 1274 | 1101 | 938 | 898 | 42 | 41 | 3638 | 3374 |
| Total | 　 | 34654 | 29483 | 22434 | 4402 | 34400 | 27760 | 10679 | 8609 | 84135 | 70254 |

Note: † – Recording time during the autumn of 2021 was two hours longer than the spring of 2022. This column presents the adjusted numbers of calls from autumn 2021 after removing calls recorded during those two extra hours, such that the numbers were comparable with those in spring 2022. ‡ – Some calls of this species may have been misidentified because of the incomplete understanding of its full variation of NFCs. § – Identification of these species based on NFCs may be uncertain. †† – Buntings were grouped together in autumn 2021 and spring 2022, but some were identified to species since autumn 2022. ‡‡ – For flycatchers, we did not count the number of their calls in autumn 2021 and spring 2022 (they were counted toward unidentified calls instead), thus had data only for autumn 2022 and spring 2023. §§ – Since autumn 2022, we adopted a more conservative approach to identifying calls of wagtails and pipits to species (i.e. where in doubt, we identified calls to the “wagtails and pipits” group rather than to individual species); hence the much higher number of calls for this group in autumn 2022 and spring 2023 compared with previous seasons.

**Table S2** The counts of bird observation checklists used to generate temporal patterns for 14 selected species or species groups recorded by NFC.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Common name | Scientific name | Birdreport | eBird | NFCs |
| **Species** |
| Olive-backed Pipit | *Anthus hodgsoni* | 2019 | 1683 | 26158 |
| Common Rosefinch | *Carpodacus erythrinus* | 353 | 448 | 7843 |
| Eurasian Skylark | *Alauda arvensis* | 818 | 809 | 4816 |
| Little Bunting† | *Emberiza pusilla* | 3227 | 2361 | 1692 |
| Brambling | *Fringilla montifringilla* | 2203 | 1636 | 1565 |
| Richard’s Pipit | *Anthus richardi* | 636 | 731 | 440 |
| Eastern Yellow Wagtail | *Motacilla tschutschensis* | 1158 | 1023 | 370 |
| Siberian Accentor | *Prunella montanella* | 416 | 327 | 305 |
| Great Bittern | *Botaurus stellaris* | 280 | 287 | 212 |
| **Species group** |
| Buntings‡ | Yellow-throated Bunting | *Emberiza elegans* | 2353 | 1423 | 6255 |
| Black-faced Bunting | *Emberiza spodocephala* | 983 | 891 |
| Tristram’s Bunting | *Emberiza tristrami* | 562 | 376 |
| Yellow-browed Bunting | *Emberiza chrysophrys* | 396 | 218 |
| Little Bunting | *Emberiza pusilla* | 3227 | 2361 |
| Flycatchers§ | Yellow-rumped Flycatcher | *Ficedula zanthopygia* | 593 | 474 | 4102 |
| Taiga Flycatcher | *Ficedula albicilla* | 3392 | 2193 |
| Dark-sided Flycatcher | *Muscicapa sibirica* | 917 | 509 |
| Asian Brown Flycatcher | *Muscicapa dauurica* | 722 | 473 |
| White-eyes | Swinhoe’s White-eye | *Zosterops simplex* | 1033 | 443 | 2693 |
| Chestnut-flanked White-eye | *Zosterops erythropleurus* | 425 | 223 |
| Thrushes | Eye-browed Thrush | *Turdus obscurus* | 304 | 171 | 1418 |
| Geese | Taiga Bean Goose | *Anser fabalis* | 735 | 261 | 1148 |
| Tundra Bean Goose | *Anser serrirostris* | 324 | 196 |
| Swan Goose | *Anser cygnoides* | 1296 | 680 |